STRUCTURAL STRENGTHENING AND EXTENDING CONCRETE STRUCTURE SERVICE LIFE USING FRP AND CORROSION INHIBITING TECHNOLOGIES – A CASE STUDY

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ABSTRACT

Concrete structures deteriorate especially when they are exposed to deleterious substances such as chloride, carbon dioxide, oxygen and moisture. This paper reports on the rehabilitation of a 34 year old concrete water treatment tank structure, which has suffered from serious concrete dilapidation and reinforcement corrosion. Any repair scheme has to address two major issues: compensating for reinforcement loss (thus restoring structural capacity) and extension of its service life. Conventional repair methods such as re-construction and rebar augmentation were costly, time-consuming and require regular maintenance. A more effective method was deployed for this project, combining the use of fibre-reinforced polymers (FRP) for structural strengthening and a proprietary corrosion inhibiting system. To monitor the effectiveness of corrosion protection by the combined FRP and corrosion inhibiting technologies, a corrosion monitoring system was also installed. Results from the monitoring showed that the corrosion risk of concrete reinforcement was significantly reduced.

KEYWORDS

FRP, concrete repair, structural strengthening, corrosion protection.

INTRODUCTION

Repair strategies for reinforced concrete structures keep evolving. Conventional rehabilitation methods such as re-construction, reinforcement augmentation and protective coating have their own limitations. Re-construction causes serious disruption to operations of structures and is expensive. Reinforcement augmentation is able to restore the structural capacity. Yet, to provide sufficient lapping to reinforcement, substantial concrete breakout and repair is required. Considerable time would be required to complete the repair. Protective coating may relieve reinforcement corrosion in the short term. However, it requires re-application regularly, usually every 5 years. The life-cycle cost would be high.

This paper reports on a case study at a water treatment works in Hong Kong where an innovative approach was adopted for the repair of reinforced concrete slab structures. This approach combined the use of fibre-reinforced polymer (FRP) technology and corrosion inhibiting technology. The FRP technology made use of a FRP to restore the structural capacity of the slab and at the same time form an insulation layer against ingress of corrosive agents. The corrosion inhibiting technology made use of proprietary corrosion inhibitors to treat both the steel reinforcement and concrete so that the steel corrosion was halted. A corrosion monitoring scheme was subsequently implemented to monitor the effectiveness of this repair method. The monitoring results of about one year show that this approach has worked very effectively and reduced the corrosion risk significantly.

INVESTIGATION

Concrete dilapidation and reinforcement corrosion are common problems in existing structures, especially for the ones constructed more than 20 years ago. Concrete defects including delamination and cracks would reduce effective concrete cover to reinforcement. The resistance of the concrete against ingress of deleterious substances such as oxygen, moisture, chloride and carbon dioxide is hence reduced, shortening the service lives
of structures. On the other hand, with reduced concrete strength and corroded reinforcement, the structural capacities would be reduced. If the deteriorations are serious, they would affect the safety of the structures, which, in extreme cases, would collapse and endanger the public.

The first batch of 6 accelerators at this water treatment works were progressively commissioned from 24 to 34 years ago (Accelerators N1, N2 and N3 were commissioned in 1973, N4 and N5 in 1976 and N6 in 1983). The concrete tank structures had suffered from structural deteriorations. The concrete hood slab at the top of Accelerator N2 had seriously deteriorated. Since the 6 accelerators were constructed at about the same time with the same structural arrangement and exposure conditions, it was important that a proper repair scheme was adopted in the first place. If successful, further repair of the same type could then make reference to this case. With this in mind, an investigation was carried out to identify the extent of the concrete defects and the degree of reinforcement corrosion. Therefore, the concrete hood slab of Accelerator N2 was chosen for investigation.

A visual inspection and a hammer tapping survey were carried out to the soffit of the hood slab. All areas with concrete defects were removed by hand held equipment. When rusts were found on exposed reinforcement surface, the reinforcements would be cleaned with all rusts removed. The diameters of the existing reinforcements in both the primary and secondary directions were then measured using callipers. The results of the reinforcement diameter survey were compared with the as-built drawings. The percentage losses of reinforcements were then established.

The concrete hood slab was a 360mm thick circular slab of 11.4m in diameter designed to span in two perpendicular directions. About 30 sq.m of 102 sq.m of the slab soffit area was delaminated. According to as-built drawings, bottom bars in both the primary and secondary direction were high yield bars of 32mm in diameter at 200mm spacing. The survey results showed that the bottom main bars and secondary bars had lost on average 30% and 15% of their cross section respectively. Using BS8110 to carry out design check, it was estimated that the rebar section losses had led to corresponding bending moment capacity losses of 25% and 12% respectively.

**CONVENTIONAL REPAIR METHODS**

There are a number of conventional repair methods available, for example, demolition and re-construction, rebar augmentation and application of protective coating. It should be noted that every proper repair scheme to the concrete hood slab has to address two major issues:- (i) compensating for reinforcement loss, so as to restore the original bending moment capacity of the slab, and (ii) extending the service life of the structure so that the structure will work properly within its remaining service life. The advantages and disadvantages of various conventional repair methods are discussed below, in the context of whether they can address the two major issues:-

*Demolition and re-construction* – This method is able to restore the slab capacity and at the same time use new concrete and reinforcement so that the materials would last for the intended design life. The method will effectively address the two major issues above. However, it would cause serious disturbance to operations during the re-construction period, and would be very expensive.

*Rebar augmentation* – This method is able to restore the slab’s structural capacity by supplementing reinforcements to the deteriorated sections. Since newly added reinforcements would need to lap with the existing reinforcement, this often proves to be difficult for extra concrete would need to be broken out in order to expose sound reinforcements. More substantial concrete repair after the rebar augmentation would consequently be required, with cost implications. In addition, the effectiveness of this method to extend the service life of the structure is dubious. Deleterious substances such as oxygen, moisture, chloride and carbon dioxide may permeate the repaired concrete and reinforcement, leading to future reinforcement corrosion and the earlier corrosion and structural deterioration may repeat.

*Application of protective coating* – The main function is that it forms a barrier on top of the concrete surface against ingress of liquids and gases such as oxygen and moisture. However, this method does not work well when the chloride ions or carbon dioxide have already penetrated into the concrete. Further, the usual design life of protective coating is only 5 years, thus re-painting is required regularly.
In the case of the concrete hood slab at Accelerator N2 at the water treatment works, a new approach was adopted, with a view to addressing the two major concerns of compensating for the reinforcement loss and extending the service life of the structure. This approach combined the use of two new technologies: viz. the use of fibre-reinforced polymers and corrosion inhibitors. The defective areas of concrete hood slab were identified and removed, followed by rust removal of corroded reinforcements. The area was repaired by patch repair. Corrosion inhibitors were applied to the whole concrete hood slab before the slab was strengthened with FRP.

Fibre-reinforced polymer (FRP) composites are flexible sheets or fabrics made of fibres in one or multiple directions. They are impregnated with epoxy to form a high tensile strength and light weight composite immune to corrosion. The FRP technique in this case was used with two purposes: structural strengthening and corrosion protection.

Strengthening of concrete slab by means of FRP is a technique which relies on the composite action between the reinforced concrete slab and the externally bonded FRP. The FRP adopted in this project was a glass fibre-reinforced polymer (GFRP) composite. The material properties of this composite are shown in the following table:

<table>
<thead>
<tr>
<th>Description</th>
<th>Typical value of the adopted GFRP composite</th>
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<tbody>
<tr>
<td>Ultimate tensile strength of glass fibres in primary direction</td>
<td>460 N/mm²</td>
</tr>
<tr>
<td>Elongation of composite fibre</td>
<td>1.67 %</td>
</tr>
<tr>
<td>Tensile modulus based on cross sectional area of primary fibres</td>
<td>26 100 N/mm²</td>
</tr>
<tr>
<td>Nominal thickness of composite</td>
<td>1.3 mm</td>
</tr>
</tbody>
</table>

As a bending moment capacity loss was found in both slab directions, the FRP strengthening was applied in both directions. It was shown by design that 2 layers (2.6mm thick in total) of GFRP composites were able to restore the 25% loss in bending moment capacity in the primary direction, while a single layer (1.3mm thick) of FRP composites was able to restore the 12% loss in bending moment capacity in the secondary direction. Figure 1 below is a schematic diagram showing the strengthening scheme using GFRP. Figure 2 shows the application of the GFRP onto the slab soffit.

![Figure 1. Schematic diagram of FRP strengthening scheme](image-url)
The GFRP composites served another function – corrosion protection by making use of the impermeable characteristics of FRP. Both the fabrics and epoxy are generically impermeable. This was verified by a water permeability test conducted on the GFRP composite. The composite was tested to DIN 1048: Part 5: 1991 and no water penetration was identified. This proved the impermeability of the GFRP composite. The GFRP composites bonded to the surface of the concrete slab formed an impermeable layer protecting the reinforced concrete from the ingress of deleterious substances such as water, moisture, chloride and carbon dioxide.

CORROSION INHIBITING TECHNOLOGY

To prevent the reinforcing the steel from further corrosion and extend the service life of the structure, a corrosion inhibiting technology was adopted. This was a corrosion inhibiting system which consisted of two components, viz. Layer 1 Volatile Corrosion Inhibitor and Layer 2 High Penetration Solution. The system makes use of both chemical and physical components to inhibit corrosion, and increase the integrity of the structure.

The Layer 1 is a vapour phase monomolecular amine system. When it is applied, it sublimes and permeates the concrete as a gas and distributes itself uniformly to form a passive film on the corroded reinforcing steel. The Layer 2 is a water-based, chemically modified silicate formulation which reacts in the matrix of the cement pores to produce a polymeric gel. This reduces the porosity of the concrete and inhibits further penetration of moisture and other deleterious substances. The application of the corrosion inhibiting system by either spray, brush or roller (Figure 3) is simple.
CORROSION MONITORING

The corrosion of steel in concrete is an electro-chemical process and, as such, the extent of steel corrosion can be assessed by measuring the steel potential using the half-cell potential technique. ASTM 876-80 recommends the following in interpreting the measurements:

<table>
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<tr>
<th>Potential w.r.t. Ag/AgCl reference electrode</th>
<th>Interpretation (probability of active steel corrosion)</th>
</tr>
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<tbody>
<tr>
<td>-230 to -380 mV</td>
<td>95%</td>
</tr>
<tr>
<td>-80 to -230 mV</td>
<td>50%</td>
</tr>
<tr>
<td>Less negative than -80 mV</td>
<td>5%</td>
</tr>
</tbody>
</table>

For this project, four corrosion monitoring probes were installed into the both apparently good and bad areas and readings were taken before and after the application of the corrosion inhibiting system (so as to verify its effectiveness). A long-term monitoring of up to two years has been planned.

The site works were completed about a year ago and the results from the corrosion monitoring work are encouraging. As shown in Figure 4, after the application of the corrosion inhibiting system, significant potential shifts, towards the beneficial side, have been registered. For the initially-corroding areas, the shift was considerable at between 263mV to 274mV. As a result, the risk of further steel corrosion is substantially reduced. For apparently good areas, a positive shift has also been recorded but not to the same magnitude. This indicates that the corrosion inhibiting system is also good as a preventive measure for concrete not suffering from corrosion.

Both the GFRP sheets and corrosion inhibiting system offer corrosion protection to the concrete hood slab. The potential readings further shifted towards the beneficial side (i.e., less negative), indicating the corrosion risks of both initially good and bad areas kept decreasing over time. With reduced corrosion risks, the service life of the slab structure is expected to be extended.

CONCLUSIONS

A reinforced concrete hood slab at a water treatment works of Hong Kong was rehabilitated with innovative methods using both fibre-reinforced polymer (FRP) and corrosion inhibitor. Based on this case study, the following conclusions may be drawn:
Two major issues have to be addressed in every repair scheme: compensating for reinforcement loss thus restoring the structural capacity and the extension of the service life of the structure. Conventional repair methods such as demolition and re-construction and rebar augmentation are costly, time consuming and require regular maintenance.

Structural repair using GFRP was able to restore the original capacity of the reinforced concrete slab structure, compensating for 30% and 15% losses in steel cross section in the bottom main bars and bottom secondary bars respectively. Bending moment capacities in these two directions were restored by 2 layers and 1 layer of GFRP composites placed on the soffit of the slab along the directions of main bars and secondary bars respectively.

In addition to restoring the bending moment capacity, the applied GFRP formed an impermeable layer on the soffit of the slab. This effectively reduced further ingress of corrosive substances such as oxygen, moisture, carbon dioxide and chloride into the concrete structure.

The corrosion inhibiting system was effective for the reinforced concrete slab. By applying these two systems, both the chemical and physical properties of the reinforced concrete were changed to enhance the corrosion resistance and achieve corrosion protection. The Layer 1 permeated into concrete and formed a passive film on the reinforcement. The Layer 2 filled voids in the concrete and inhibited further penetration of moisture and other deleterious substances.

To demonstrate the effectiveness of this repair approach, a corrosion monitoring system using embedded silver/silver chloride reference electrodes was implemented. Results of the corrosion monitoring were interpreted in accordance with ASTM-876-80. Both initially corroding areas and apparently good areas showed immediate reduction in corrosion risks after the application of the corrosion inhibiting system. The corrosion risks of both areas kept decreasing over time. As a result, the service life of the slab structure was extended.

From the corrosion monitoring results, it can be concluded that the corrosion protection offered by this repair scheme using FRP and corrosion inhibiting technologies is effective. In view that this scheme addresses both of the 2 major issues of compensating for reinforcement loss and extending of service life of structure, this scheme would provide a comprehensive solution in fighting against the deterioration of aging reinforced concrete structures.

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REFERENCES